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CASE STUDY • DISCUSSION ARTICLE • AUSTRALIAN AUTOMOTIVE COMPONENT

# Life cycle assessment of Australian automotive door skins

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**Abstract**

*Background, aim, and scope* Policy initiatives, such as the EU End of Life Vehicle (ELV) Directive for only 5% landfilling by 2015, are increasing the pressure for higher material recyclability rates. This is stimulating research into material alternatives and end-of-life strategies for automotive components. This study presents a Life Cycle Assessment (LCA) on an Australian automotive component, namely an exterior door skin. The functional unit for this study is one door skin set (4 exterior skins). The material alternatives are steel, which is currently used by Australian manufacturers, aluminium and glass-fiber reinforced polypropylene composite. Only the inputs and outputs relative to the door skin production, use and end-of-life phases were considered within the system boundary. Landfill, energy recovery and mechanical recycling were the end-of-life phases considered. The aim of the study is to highlight the most environmentally attractive material and end-of-life option.

*Methods* The LCA was performed according to the ISO 14040 standard series. All information considered in this study (use of fossil and non fossil based energy resources, water, chemicals etc.) were taken up in in-depth data. The data for the production, use and end-of-life phases of the door skin set was based upon softwares such as SimaPro and GEMIS which helped in the development of the inventory for the different end-of-life scenarios. In other cases, the inventory was developed using derivations obtained from published journals. Some data was obtained from GM-Holden and the Co-operative research Centre for Advanced Automotive Technology (AutoCRC), in Australia. In cases where data from the Australian economy was unavailable, such as the data relating to energy recovery methods, a generic data set based on European recycling companies was employed. The characterization factors used for normalization of data were taken from (Saling et. al. Int J Life Cycle Assess 7(4):203–218 2002) which detailed the method of carrying out an LCA.

*Results* The production phase results in maximum raw material consumption for all materials, and it is higher for metals than for the composite. Energy consumption is greatest in the use phase, with maximum consumption for steel. Aluminium consumes most energy in the production phase. Global Warming Potential (GWP) also follows a trend similar to that of energy consumption. Photo Oxidants Creation Potential (POCP) is the highest for the landfill scenario for the composite, followed by steel and aluminium. Acidification Potential (AP) is the highest for all the end-of-life scenarios of the composite. Ozone Depletion Potential (ODP) is the highest for the metals. The net water emissions are also higher for composite in comparison to metals despite high pollution in the production phases of metallic door skins. Solid wastes are higher for the metallic door skins.

*Discussion* The composite door skin has the lowest energy consumption in the production phase, due to the low energy requirements during the manufacturing of E-glass and its fusion with polypropylene to form sheet molding compounds. In general, the air emissions during the use phase are strongly dependent on the mass of the skins, with higher emissions for the metals than for the composite. Material recovery through recycling is the highest in metals due to

Discussion contributions to this article from the readership would the highly welcome. The authors

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efficient separation techniques, while mechanical recycling is the most efficient for the composite. The heavy steel skins produce the maximum solid wastes primarily due to higher fuel consumption. Water pollution reduction benefit is highest in case of metals, again due to the high efficiency of magnetic separation technique in the case of steel and eddy current separation technique in the case of aluminium. Material recovery in these metals reduces the amount of water needed to produce a new door skin set (water employed mainly in the ingot casting stage). Moreover, the use of heavy metals, inorganic salts and other chemicals is minimized by efficient material recovery.

*Conclusions* The use of the studied type of steel for the door skins is a poor environmental option in every impact category. Aluminium and composite materials should be considered to develop a more sustainable and energy efficient automobile. In particular, this LCA study shows that glass-fiber composite skins with mechanical recycling or energy recovery method could be environmentally desirable, compared to aluminium and steel skins. However, the current limit on the efficiency of recycling is the prime barrier to increasing the sustainability of composite skins.

*Recommendations and perspectives* The study is successful in developing a detailed LCA for the three different types of door skin materials and their respective recycling or end-of-life scenarios. The results obtained could be used for future work on an eco-efficiency portfolio for the entire car. However, there is a need for a detailed assessment of toxicity and risk potentials arising from each of the four different types of door skin sets. This will require greater communication between academia and the automotive industry to improve the quality of the LCA data. Sensitivity analysis needs to be performed such as the assessment of the impact of varying substitution factors on the life cycle of a door skin. Incorporation of door skin sets made of new biomaterials need to be accounted for as another functional unit in future LCA studies.

**Keywords** Acidification potential (AP) · Aluminium · Automotive door skins · Composite material · Energy recovery · Global warming potential (GWP) · Landfill · Life cycle assessment (LCA) · Mechanical recycling · Ozone depletion potential (ODP) · Photo oxidants creation potential (POCP) · Steel

## 1 Background, aim, and scope

The increased awareness of the importance of environmental protection, and the possible impacts associated with products, both manufactured and consumed, has increased interest in the development of methods to better understand and address these impacts. One of the methods for this purpose is Life Cycle Assessment (LCA). LCA addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use and end of life treatment, recycling and final disposal (i.e. cradle to grave) (Munoz et. al. 2006).

When this assessment is combined with eco-efficiency analysis which aims at comparing the relative costs and environmental impacts of different technologies, the most eco-efficient technology representing low cost and environmental burden can be determined (Saling et al. 2002). Only LCA development is addressed in this study.

Over 500,000 vehicles enter the waste stream each year in Australia based on an information paper by Environment Australia 2002 (Environmental Impact of End-of-Life Vehicles). The volume of ELVs is likely to increase at an escalating rate as a result of the continuing upward trend in the rate of vehicle ownership, the decreasing average age of vehicles, and the declining cost effectiveness of owning older vehicles. Given these trends, it is conceivable that the number of ELVs might exceed 750,000 per year by 2010. Moreover, only 65 to 70% of ELVs by weight are currently being recycled in Australia which represents the metal fraction of an ELV only, mainly steel. The remaining 30 to 35%, the so called Automobile Shredder Residue (ASR), consisting of plastics, fibers, glass; paint etc. is currently being landfilled. In order for the Australian cars to be internationally competitive, there is a great challenge to meet the EU ELV Directive requirements of only 5% landfilling by the year 2015. (Directive 2000/53/EC of the European Parliament and of the Council)

Furthermore, an era of energy crisis across the world and high oil price has put tremendous pressure on making lightweight cars with higher fuel economy and lower environmental impact such as low greenhouse gas emissions, lower energy consumption. This struggle between higher recyclability and higher fuel economy, environmental friendliness or sustainability of cars is one of the main driving forces for this study aiming at assessing the different material alternatives for door skins of ELVs and end-of-life treatments, so as to determine the most sustainable material and recycling technology. The whole car shredding process (after depollution and the removal of components destined for reuse) followed by recycling of metals and landfilling of the residues has become established as a standard ELV treatment in Australia due to low landfilling costs (Environment Impact Paper: Environment Australia 2002). This study also aims to assess this current methodology critically and attempts to suggest alternatives which could be further testified by thorough research.

Door skins are one of the major parts of the car that have continued to be manufactured from steel as of today. With

increasing oil price and a need for improving the fuel economy, door skins manufactured from different materials form attractive parts to be subjected to a life cycle assessment in order to obtain a clear environmental picture of the performance of different materials. Moreover, they can be easily dismantled and thus the data for the development of life cycle analysis can be easily computed. Due to the complexity in the life cycle of door skins ranging from production to their waste treatment phases, system boundary formulation is employed to consider the significant processes as per ISO 14040 (2006): Environmental Management—Life Cycle Assessment—Principles and Framework. This is shown in Fig. 1 for steel, aluminium and composite door skins along with respective recycling technologies.

At each phase of the life cycle, consumption of raw material resources and fossil/non-fossil based energy is evaluated. The resulting emissions to air, water and the solid wastes generated are evaluated. This forms the Life Cycle Inventory data for door skins of different materials and different recycling technologies.

Based on ISO 14040, there are three main impact categories. The first is total energy consumption measured in MJ of energy. The second is total raw material or resources consumption, measured by scaling the amount of each raw material used in the life cycle of door skin by the raw materials' characterization factor. The third is emissions; air, water and solid wastes. Air emissions are further divided into four sub-categories which include, Global Warming Potential measured in kg. of $CO_2$, Acidification Potential (AP) measured in kg. of $SO_2$, Photo Oxidants Creation Potential (POCP) measured in kg. of ethene equivalent gases and Ozone Depletion Potential (ODP) measured in kg. of halogenated hydrocarbons.

## 2 Goal and scope

The goal of this paper is to determine the most environmentally acceptable material alternative along with the recycling technology for door skins of cars. Three material alternatives are considered in this study; steel aluminum and glass-fiber polypropylene composite. Steel is used by many manufacturers worldwide and is the only material used by Australian manufacturers. Aluminum has been used in the chassis by Jaguar and Audi. Recyclable glass-polypropylene composites (with 60% glass content by weight), such as those produced by Vetrotex Inc. or Quadrant Plastic Composites AG, could be used for automotive components.

The characteristics of door skins based on these materials are summarized in Table 1. The functional unit in this study is one door skin set (4 exterior skins) with fixed volume and size. The substitution factor then adjusts the mass of each skin set based on differences in material densities and mechanical properties but keeping fixed volume. The reference in this study is the 17 kg door skin set made of steel (data supplied by GM Holden., Australia).

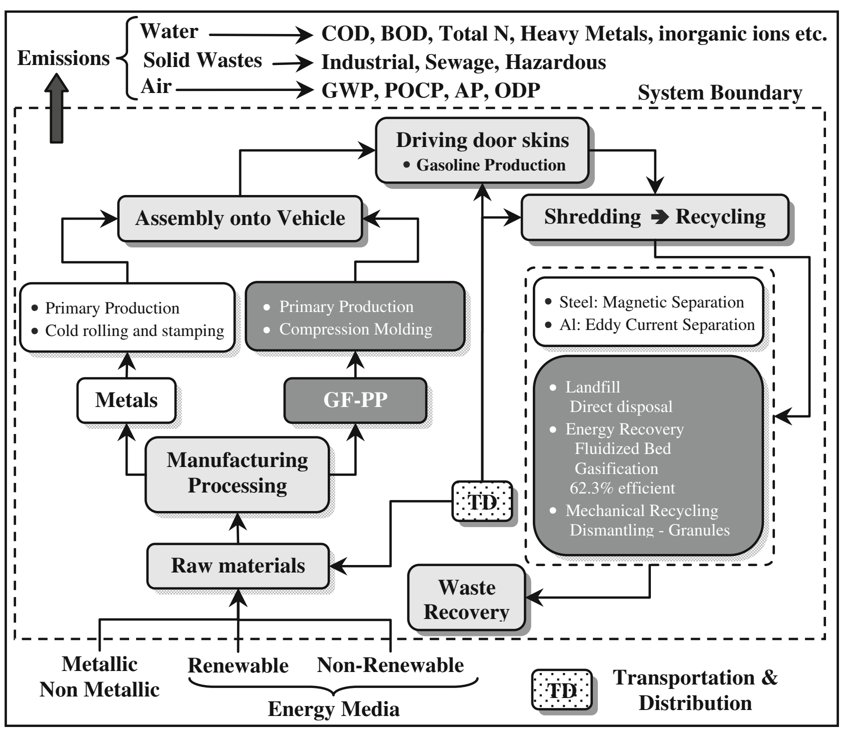

Fig. 1 System boundary and impact categories for LCA of door skin sets

**Table 1** Characteristics of door skin set

| Characteristic of Door Skin Set | Steel | Al. | GFPP |
|---|---|---|---|
| Material Substitution Factor | 1 | 0.55 | 0.69 |
| Mass of door sets (4 door skins) *(kg)* | 17.0 | 9.35 | 11.7 |
| Total mass of the car *(kg)* | 1381 | 1374 | 1376 |
| Fuel Efficiency *(km/l)* | 11.31 | 11.67 | 11.56 |
| Lifetime fuel consumed by car *(l)* | 13264 | 12853 | 12976 |
| Lifetime fuel consumed by skin set *(l)* | 163 | 87 | 111 |

This is because all current door skin sets in Australia are predominantly made of steel. The substitution factor represents the minimum amount of material B needed to substitute material A in order for the functionality of the component to be maintained after substitution has taken place. In this study, the functionality is the strength of the door skin. The fuel efficiencies for each door skin design were then determined using the fuel efficiency of the steel skin (11.31 km/l) as the base case. The difference in fuel efficiency between the material alternatives is minimal. However, there is a significant difference in fuel consumption for each door skin design over the entire life of the car. This is assumed to be 150,000 km for the lifetime fuel consumption data presented in Table 1 based on (Makuta et. al. 2000).

The scope of the study was to qualify and quantify the main environmental aspects of the door skin life cycle in the Australian context. Thus, the users of the information provided by this study are the automotive manufacturers, mainly GM Holden Australia, Melbourne. The results will also be useful in establishing environmental sustainability best practice for local automotive suppliers, automotive recyclers, automotive associations and Australian government agencies.

## 3 Methods

This study was conducted in accordance with ISO 14040 (2006): Environmental Management—Life Cycle Assessment—Principles and Framework. The impact categories selected for the study were based on the ISO inventory categories. The top level categories were energy consumption, raw material consumption and emissions. The emissions category comprised solid wastes, water (in terms of pollutants that enter water resources) and air emissions. The air emissions included all emissions that result during the door skin set life cycle; namely, emissions with global warming potential (GWP), photo-oxidants creation potential (POCP), acidification potential (AP) and ozone depletion potential (ODP). All information considered in this study (use of fossil and non fossil based energy resources, water, chemicals etc.) were taken up in in-depth data.

The software programs SimaPro and Global Emission Model for Integrated Systems (GEMIS), Version 4.3, were used to develop the LCA inventory, shown in Table 2. In other cases, the inventory was developed using derivations obtained from published journals. In cases where data from the recycling in automotive industry of Australia was unavailable, such as the data relating to energy recovery methods, a generic data set based on European recycling companies was employed (Fussler 1999). This was based on the assumption of slight variations in transportation and distribution in case such European recycling technologies would be started in Australia. This difference and the environmental impact were accounted in the LCIA based on Australian transportation data. The characterization factors used for normalization of data were taken from Saling et al. (2002); Rydh and Sun (2005), Hendrix et al. (1996). These factors account for the amount of reserves and the rate of resource depletion, which is significant for fossil fuels. This explains the large energy benefit in the mechanical recycling of GFPP, compared to the production phase, after the 150,000 km lifetime. The energy consumed is dominated by petroleum, which has the highest characterization factor due to relatively low reserves and high depletion rate.

In conventional recycling of fiber reinforced composites, the composite is said to have been recycled when the long fibers that are precipitated during mechanical recycling are reused in making the same product. This approach limits the recycling rate. In this study however, it has been assumed that all precipitated fibers are either reused in making door skins or in making other products such as Chopped Strand Mats where the fiber strength requirements are less stringent. The matrix is converted back into pellets and reused in making door skins. This new approach should translate into much higher realistic and attainable recycling/reuse rates for plastics and thus greater energy benefit upon recycling.

## 4 Results and discussion

The inventory data is summarized through the use of characterization factors, and by combining the inventory

**Table 2** LCA data for the three material options for Australian automotive door skins

| Cat. | Sub-Cat. | Steel | | | Aluminum | | | GFPP | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Prod. | Use | Rec. | Prod. | Use | Rec. | Prod. | Use | L | ER | MR |
| Energy (MJ) | Coal | 359 | 46 | −273 | 1183 | 25 | −255 | 22 | 32 | 0 | −13 | 51 |
| | Petroleum | 75 | 6119 | −39 | 140 | 3279 | −489 | 160 | 4146 | 1 | −7 | −220 |
| | Natural Gas | 43 | 91 | 7 | 351 | 49 | −489 | 32 | 61 | 0 | −4 | −83 |
| | Renewables | 98 | 35 | 5 | 90 | 19 | 0 | 18 | 24 | 0 | 0 | 22 |
| | Total | 575 | 6291 | −301 | 1777 | 3376 | −1233 | 232 | 4263 | 1 | −24 | −230 |
| Material (kg) | Water | 3663 | 299 | −30 | 542 | 160 | −71 | 182 | 203 | 0 | 0 | −15 |
| | Coal | 17 | 0 | −15 | 0.690 | 0 | −14 | 4 | 0 | 1E-03 | −0.712 | 1.947 |
| | Crude oil | 4.1E-05 | 0.011 | −0.926 | 9.78E-06 | 6E-03 | −11 | 12 | 0.007 | 0.050 | −0.174 | −5.068 |
| | Natural gas | 7.E-03 | 0.001 | 0.153 | 0.020 | 0.00055 | −11 | 7 | 0.00069 | 0 | −0.121 | −2.249 |
| | Metallic Ores | 29 | 2.210 | −18.235 | 45 | 1.184 | −25 | 0.054 | 1.497 | 0 | 4.959E-07 | 0.00 |
| | Non-metallic | 3.E-04 | 1.242 | −0.477 | 4.157 | 0.666 | 0 | 0.424 | 0.842 | 0 | −0.007 | 0.022 |
| | Salts | 0 | 0 | 0 | 0 | 0 | −0.511 | 0.446 | 0 | 0 | 0.001 | −0.024 |
| | Ceramics | 8 | 0 | −4.339 | 4.419 | 0 | −0.00017 | 2.432 | 0 | 0 | 0.028 | 0.00 |
| Emissions Air / (kg) | $CO_2$ | 41 | 467 | −25 | 162 | 250 | −68 | 42 | 317 | 1 | 11 | −36 |
| | $SO_X$ | 0.067 | 0.314 | −0.046 | 1.063 | 0.168 | −0.496 | 0.349 | 0.213 | 0.000419 | −0.013 | −7.E-03 |
| | $NO_X$ | 0.085 | 0.389 | −0.024 | 0.467 | 0.212 | −0.141 | 0.298 | 0.267 | 2.E-03 | −2.E-03 | −0.027 |
| | $HC_S$ | 0.192 | 0.222 | −0.131 | 0.103 | 0.119 | 4.E-03 | 0.144 | 0.150 | 0.143 | −6.E-03 | 4.E-03 |
| | C1. HC. | 3E-03 | 0.00 | 1E-03 | 8E-03 | 9.1E-05 | −5.E-03 | 4E-03 | 2.E-03 | 7.15E-07 | −0.000495 | 1.E-03 |
| | Particulates | 0.037 | 0.024 | −2E-03 | 0.292 | 0.013 | −0.197 | 0.120 | 0.016 | 0.00016 | −3.E-03 | 7.E-04 |
| | Heavy Metals | 0.0001 | 0.00029 | 0.000315 | 1.15E-06 | 0.00016 | −2.E-03 | 0.00017 | 0.0002 | 2.74E-06 | −0.00013 | 4.E-04 |
| | Others | 0.532 | 2.847 | −0.213 | 1.561 | 1.561 | −0.679 | 0.035 | 1.959 | 2.E-03 | −0.00031 | −0.045 |
| Water (0.001 kg) | COD | 2.E+00 | 36.3741 | 0.738 | 185.695 | 19.464 | −0.76355 | 3.453 | 24.648 | 0.00723 | −0.0097 | −1.871 |
| | BOD | 2.E-01 | 1.195 | 0.289 | 7.334 | 0.64024 | −0.03073 | 0.564 | 0.80949 | 0.000221 | −0.000531 | −0.285 |
| | N-tot | 5.E-03 | 1.044 | −0.048 | 0.000 | 0.55939 | −0.56932 | 0.165 | 0.70726 | 0.005283 | −0.007753 | −0.012 |
| | NH4 | 6.E-02 | 0 | −0.046 | 0.000 | 0 | −0.6967 | 0.082049 | 0 | 0.172 | −0.014 | 0.027 |
| | PO4 | 4E-02 | 0.018 | −1.411 | 3.8E-06 | 0.00953 | −1.32488 | 0.172951 | 0.01206 | 9.44E-05 | −0.065 | 0.215 |
| | $AO_X$ | 2.E-04 | 0.001 | −0.008 | 2.42E-06 | 0.0007 | −0.00198 | 1.2E-06 | 0.00089 | 9.65E-06 | −2.98E-05 | −0.00024 |
| | Heavy Metals | 4.E+00 | 4.2E-10 | −37.288 | 5.06E-11 | 2.3E-10 | −40.099 | 4.759 | 2.9E-10 | 0.303 | −2.881 | −21.626 |
| | HC | 0.E+00 | 0 | −0.031 | 0 | 0 | −0.50367 | 2.567 | 0 | 3.630 | −0.007688 | −1.24701 |
| | SO42- | 7.E+00 | 0 | −84.705 | 0 | 0 | −10.212 | 1.251 | 0 | 0.511 | −12.382 | −40.2609 |
| | CI- | 7.E+00 | 0 | −132.517 | 0 | 0 | −50.675 | 7.674 | 0 | 1.325 | −11.622 | 1.167 |
| | Inorg Salts | 1.E-03 | 23.7964 | −73.779 | 43.431 | 12.753 | 11.3509 | 0.0098 | 16.125 | 0 | −8.113 | 33.95908 |
| Solid Wastes (kg) | Municipal | 9.E-04 | 0.09 | 0 | 3.E-03 | 0.047 | −0.010 | 8.12E-09 | 0.06 | 1.567 | −0.389 | −0.076 |
| | Construction | 85 | 14 | 0 | 254 | 7.269 | 0 | 1.741 | 9.190 | 0 | −6.678 | 0 |
| | Industrial | 8.3 | 1.1 | −0.77 | 18 | 0.596 | −9.063 | 0.366 | 0.754 | 0 | 0 | −6.E-03 |
| | Hazardous | 1E-05 | 9.7E-06 | 1.2 | 5.77E-06 | 5.2E-06 | −1.560 | 0.000246 | 6.6E-06 | 0 | 0 | −0.067 |

data with respect to each impact category. The results for door skins made from each material are shown in Figs. 2, 3, 4, 5, 6, 7, 8, 9. Results for the composite (GFPP) are given for the landfill (L), energy recovery (ER) and mechanical recycling (MR) end-of-life scenarios.

## 4.1 Energy and raw material consumption

Steel had the highest net energy and raw material consumption, as shown in Figs. 2 and 3, respectively. The energy consumption for the steel is dominated by the use phase, due to the high mass of the door skins, and with little energy recovery. Aluminium (Al) has higher energy consumption during the production and use phases, compared to the composite, but highest energy recovery. The composite skins on the other hand has minimum energy consumption in the production phase, most likely due to the low energy requirements during the manufacturing of E-glass (Borosilicate lime alumina glass fibers) and its fusion with polypropylene to form sheet molding compounds (Barbero 1998). However, the composite skins have relatively high energy consumption in the use phase in comparison to aluminium. This is due to the slightly higher mass of composite skins giving a lower fuel economy (Munoz et al. 2006). The final result is that aluminium and composite have a net energy consumption that is 35–45% lower than for steel. The raw material consumption is dominated by the production phase and is highest for the metals. Aluminium has highest consumption because of the high electricity consumption in electrolysis of alumina and wastage of raw materials during stamping and blanking to manufacture door skins. Otherwise, the trends are the same as for energy consumption.

The recycling phase shows that raw material and energy recovery in metals is more than that in composites as a

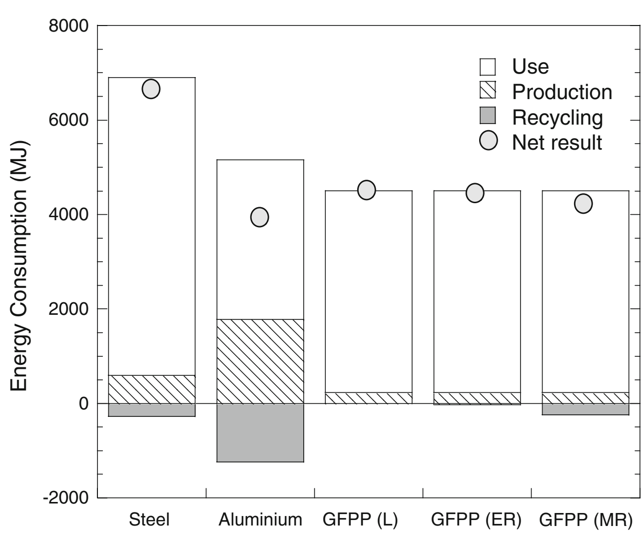


**Fig. 2** Normalized and weighted energy consumption

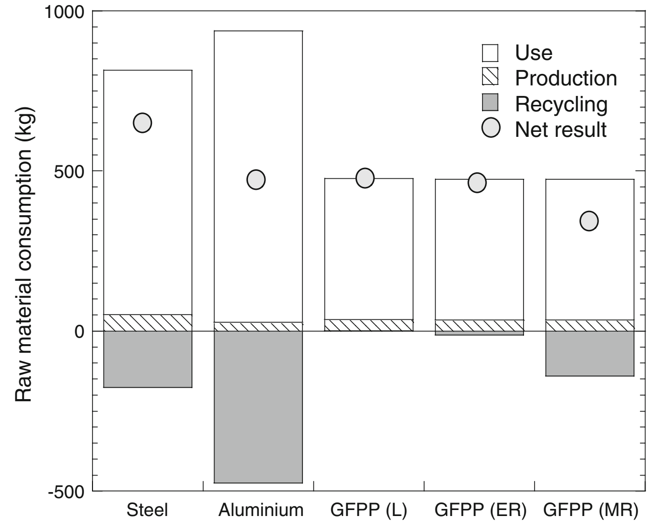


**Fig. 3** Normalized and weighted raw material consumption

result of more than 99% efficient recycling processes as supported by Hill (1996). Landfilling results in a loss of material and energy, thus representing, an unsustainable recycling strategy. However, it should be noted that for reduced environmental impact, Schmidt et al. (2004) concluded that reducing vehicle weight is more important than designing or, in this case selecting material, for a particular recycling option.

## 4.2 Air emissions

Results for global warming potential (GWP), Fig. 4, show a similar trend to the energy consumption results in Fig. 2. This is because GWP is also strongly related to the mass of the door skin, and hence fuel consumption. Although aluminium has lower net GWP than steel, it produces the maximum GWP in the production phase because of the

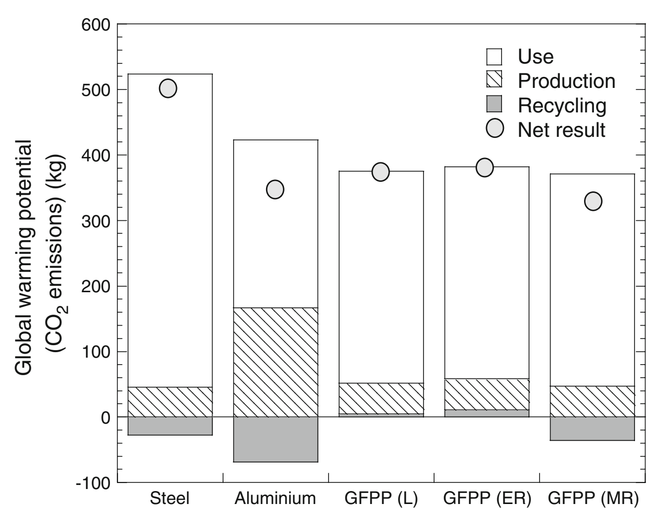


**Fig. 4** Normalized and weighted global warming potential (GWP)

high electricity consumption required for the electrolysis of alumina. Based on the information paper by Environment Australia 2002 (Environmental Impact of End-of-Life Vehicles), the proportion of electricity production from coal in Australia is higher than other forms. This accounts for the high greenhouse gas emissions. However, GWP in the use phase is lowest for aluminium as it is the most lightweight door skin set material. For the composite, the landfill scenario gives a positive value representing an increase in the emissions resulting from the deterioration of the material. It is also notable that the benefit through energy recovery method no longer represents a negative value on the graph.

The composite with landfill scenario has the highest photo oxidants creation potential (POCP) and acidification potential (AP), Figs. 5 and 6 respectively, due to material deterioration in the landfill. POCP in the production is highest for Steel due to the large amount of nitrogen oxides produced from the oxidation of coke and burning of fuel oil in blast furnace. It is also highest in the use phase, again due to high mass. However, POCP reduction benefit is at a maximum for steel. This is due to the almost 99% efficiency of magnetic separation technique as supported by Hendrix et al. (1996). The use of recycled steel captured by this efficient recovery method for new door skins reduces the amount of energy needed to produce new door skins from virgin material. The POCP benefit for aluminium skins is lower than that of steel skins, however, this is balanced by lower POCP of aluminium skins in the production and the use phase of the door skin set.

For the composites, the benefit through energy recovery method exceeds the benefit attained from mechanical recycling. Energy recovery decreases the POCP (as seen by the negative value), unlike mechanical recycling which

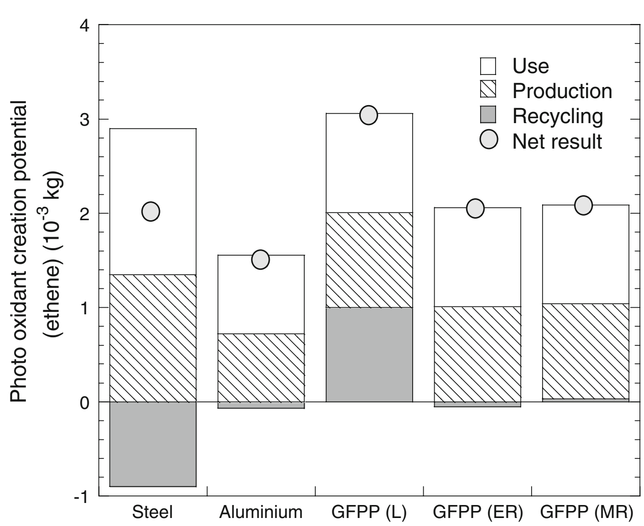


**Fig. 5** Normalized and weighted photo oxidants creation potential (POCP)

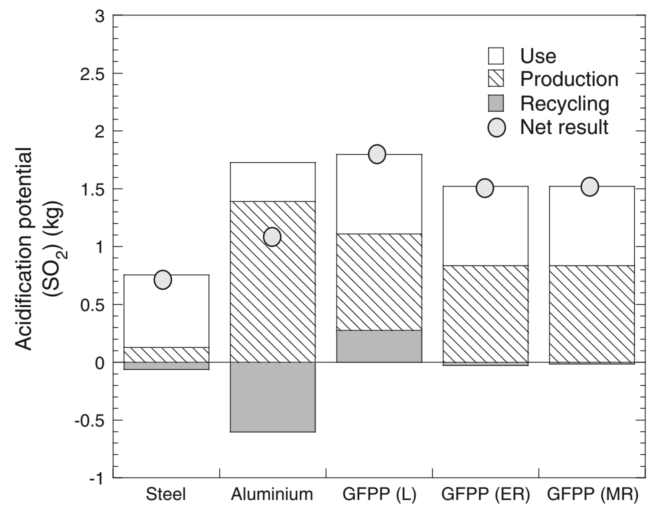


**Fig. 6** Normalized and weighted acidification potential (AP)

increases the POCP (as seen by the positive value). The operation of mechanical recyclers involves the use of electricity at a rate greater than that employed in energy recovery technology. Electricity generation in the context of Australia is carried out using thermal combustion of fuel oil and coal which are both the major sources of photo oxidants in the atmosphere.

Results for acidification potential (AP), Fig. 6, show a similar trend to POCP results for similar reasons. The AP for aluminium production is high due to the electricity consumption in the electrolysis of alumina, which produces acidic gases; sulphur dioxides, nitrogen oxides and ammonia. No definite trend exists in the three end-of-life scenarios for the composites. However, the mechanical recycling option gives a higher benefit over the energy recovery scenario. Energy recovery is only 62.33% efficient, and therefore converts a portion of the material into acidic pollutants. The benefits attained from mechanical recycling of the composite reduce as a result of some wastages occurring in precipitation of fibers from the polypropylene matrix. (Poulakis et al. 1997)

Ozone depletion potential (ODP) (Fig. 7) shows very different results to the other air emission categories. Net ODP is the highest for aluminium and steel skins. The composite skins have minimal ODP in the production phase and have a net benefit in the energy recovery and mechanical recycling end-of-life scenarios. The higher ODP for metals is due to the production of larger amounts of chlorinated hydrocarbons in the production phase. The use phase of the cars no longer adds to the ozone depletion potential due to the reduction of branched and chlorinated hydrocarbons in the gasoline employed. As a result, slight traces of chlorinated hydrocarbons released from the combustion of gasoline are insignificant to the calculations.

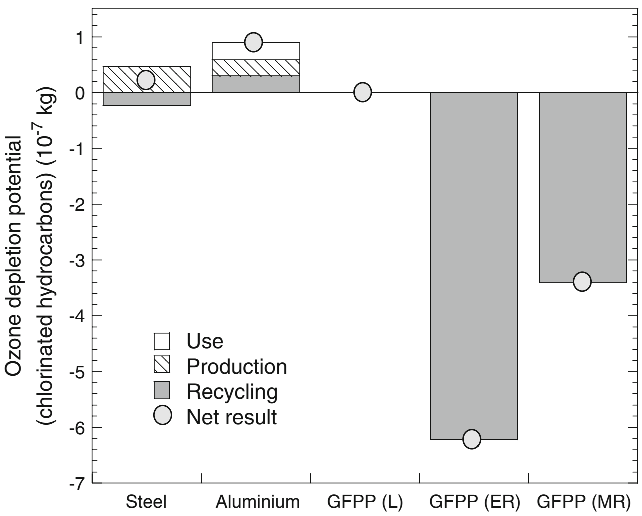


**Fig. 7** Normalized and weighted ozone depletion potential (ODP)

4.3 Water emissions

Results for water emissions, presented in terms of pollution, are shown in Fig. 8. Net water emission is the highest for landfill option for the composite skin. Aluminium and steel skins result in maximum benefit, followed by the mechanical recycling scenario for the composite. The maximum water emissions in the production phase occur in the case of the composite door skin due to the production of E-glass fibers. This process requires large amounts of heavy metals, ammonia and sulphate ions which are the major reasons for the pollution of water resources (Barbero 1998).

Water pollution reduction benefit is highest in case of metals. This results from almost 99% efficiency of both magnetic separation technique in the case of steel and eddy current separation technique in the case of aluminium (Hendrix et al. 1996). Material recovery in these metals reduces the amount of water needed to produce a new door skin set (water employed mainly in the ingot casting stage). Moreover, the use of heavy metals, inorganic salts and other chemicals is minimized by efficient material recovery. Emission reduction benefit (measured by the extent of the negative value in recycling phase) is less for the composite, with a minimum for the landfill option. Landfill scenarios give a positive value representing an increase in the emissions resulting from the deterioration of the material left in open landfills.

4.4 Solid wastes

Net solid waste (Fig. 9) is highest for the aluminium and steel due to scrap produced during the stamping and blanking processes. For composites on the other hand, the use of compression molding processes and sheet molding compound starter material minimizes waste (Poulakis et al. 1997; Hill 1996). In the use phase of the cars, as observed earlier, heavy steel skins produce the maximum solid wastes primarily due to higher fuel consumption. The composite skins also have similar rates of emissions in the use phase in comparison to aluminium. Once again, this results from a slightly higher mass of glass fiber skins giving a lower fuel economy, higher fuel consumption and greater amount of solid wastes generation.

## 5 Conclusions

The production phase results in maximum raw material consumption in all material alternatives, and is higher for metals than the glass-fiber composite. Material recovery through recycling is the highest in metals while mechanical recycling is the most efficient for the composite. Energy

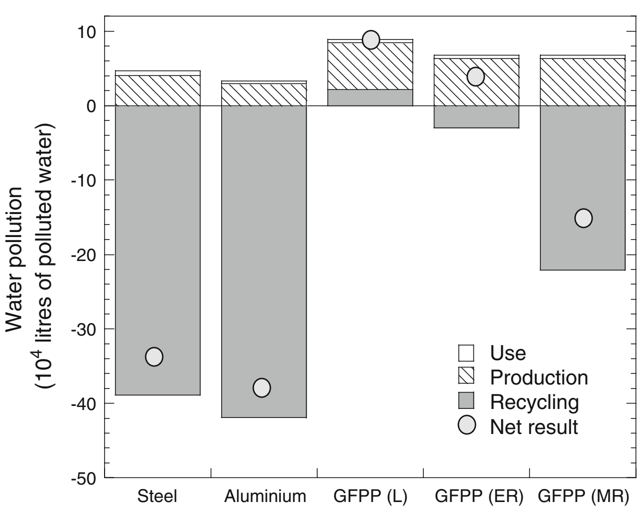


**Fig. 8** Normalized and weighted water pollution

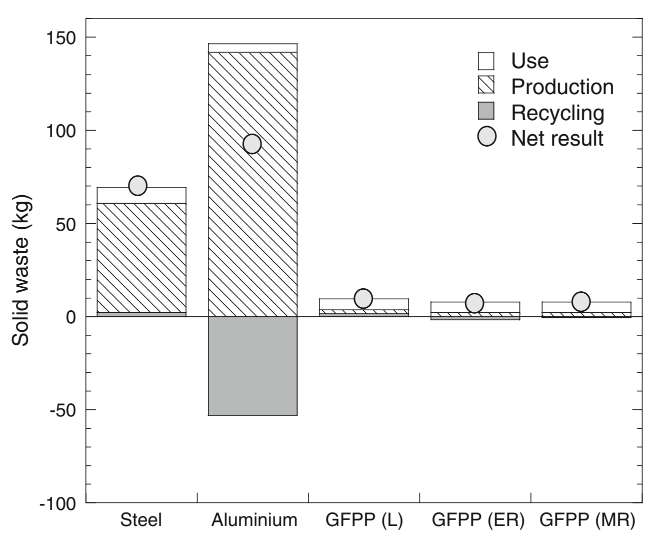


**Fig. 9** Normalized and weighted solid wastes

consumption is highest in the use phase of the door skin set, with maximum for steel followed by the composite, and then aluminium. The production phase in aluminium consumes the maximum energy. Global Warming Potential (GWP) also follows a trend similar to that of energy consumption. Photo Oxidants Creation Potential (POCP) is the highest for landfill scenario of GFPP, followed by steel and aluminium. Acidification Potential (AP) is the highest for all the recycling scenarios of composite, i.e. landfill, energy recovery and mechanical recycling. Ozone Depletion Potential is similar for all materials. The net water emissions are also higher for composite in comparison to metals despite high pollution in the production phases of the metal door skins. Solid wastes arise in larger quantities from the metal door skins. The landfill option for the composite produces the maximum wastes over the life cycle of the door skin set.

It is seen from the LCA development that conventional steel, which is currently being employed in most cars for door skin panels, is a poor environmental option in every impact category. Aluminium and composite materials should be considered to develop a more sustainable and energy efficient automobile. The current limit on the efficiency of recycling is the prime barrier to increasing the sustainability of composite skins. The landfill option for composite skins is an unfavourable option due to its negative impact on material recovery. Energy recovery seems to be inefficient in comparison to mechanical recycling option for plastics. However, this LCA study shows that glass-fiber composite skins with mechanical recycling or energy recovery method could be environmentally desirable, compared to aluminium and steel skins.

## 6 Recommendations and perspectives

The study is successful in developing a detailed LCA for three different door skin materials and their respective recycling scenarios. However, there is a need for a detailed assessment of toxicity and risk potentials arising from each of the four different types of door skin sets. This will require greater communication between the academia and the automotive industry to improve the quality of the LCA data. Sensitivity analysis needs to be performed such as the assessment of the impact of varying substitution factors on the life cycle of a door skin. Incorporation of door skin sets made of new biomaterials need to be accounted for as another functional unit in future LCA studies.

The decision of the most sustainable material alternative along with the corresponding recycling technology cannot be answered until the cost of the life cycle processes of door skin are combined together. Future work will develop an eco-efficiency portfolio in order to determine the most eco-efficient material and recycling strategy. The LCA data present here will be used to determine the environmental and economic burden of each material in an eco-portfolio. Future work should also investigate the use of all-polymer body structures and the crash behaviour of all materials that are possible alternatives to the commonly used metals.

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